COMPILATION GEOLOGIC MODEL FOR ST. LOUIS RIVER WATERSHED: A PILOT PROJECT

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Executive Summary

This report is a summary of year one of a two-year pilot project conducted by the Minnesota Geological Survey (MGS) for the Minnesota Department of Health (MDH) Groundwater Restoration and Protection Strategies (GRAPS) program designed to support watershed planning efforts. Our goal was to provide a compilation of both surface and subsurface geologic data within selected Board of Water and Soil Resources (BWSR) One Watershed One Plan (1W1P) boundaries in a format suitable for both modelers and the general public. This report focuses on the St. Louis River Watershed in northeastern Minnesota. Geologic data for the Zumbro River Watershed were also compiled in year one and are presented in a separate report (Steenberg and others, 2021).

The GRAPS program helps local planning efforts prioritize groundwater quality and quantity concerns and provides strategies and actions for protection and restoration (https://www.health.state.mn.us/communities/environment/water/cwf/localimplem.html#HowDoesGRAPS). An MDH GRAPS report is a collection of maps and data describing conditions in a watershed. Eighteen watersheds in Minnesota currently have a GRAPS report for local organizations to use for developing their watershed plans. Many state agencies (Board of Water and Soil Resources (BWSR); Minnesota Department of Agriculture (MDA); Minnesota Department of Natural Resources (MNDNR); Minnesota Pollution Control Agency (MPCA)) work together to gather data and create these reports collaboratively. General geologic information exists in these reports, but not the most detailed information available from the MGS.

The MGS is a nonregulatory research and service arm of the School of Earth and Environmental Sciences at the University of Minnesota. MGS leads a variety of mapping and research activities for the state of Minnesota to support the stewardship of water, land, and mineral resources. The MGS County Geologic Atlas (CGA) mapping program produces maps that depict the distribution of sediments and rocks in the subsurface and define their boundaries and geologic names (https://cse.umn.edu/mgs/county-geologic-atlas). Our detailed mapping program is widely used and recognized in the state. However, when planning at larger scales that involve several counties (i.e., a watershed), it can be problematic for users to create seamless geologic and hydrogeologic datasets in a GIS environment. This pilot project was set up to address this need for the GRAPS program.

Seamless geologic products across the St. Louis River Watershed are based on previously published CGAs, in-progress CGA mapping and new mapping in areas where CGA mapping has not been completed yet. Revisions were made along boundaries to achieve consistency across the watershed. Compilation methods and limitations associated with the subsurface modeling processes are described. These products were transferred into a web-based 3D model (https://arcg.is/1mbDPC) so they could be readily visualized and used outside of a GIS environment by water planners, other state agencies involved in the GRAPS process, and the public. Geologic datasets are provided in the supplementary files of this report in a format suitable for groundwater-surface water modeling. All features are documented with metadata. Basic instructions on how to use the web-based 3D model are also provided in this report.

Introduction

The goal of the Minnesota Geological Survey (MGS) and Minnesota Department of Health (MDH) Groundwater Restoration and Protection Strategies (GRAPS) two-year pilot project was to provide a compilation of both surface and subsurface geologic data within selected Board of Water and Soil Resources (BWSR) One Watershed One Plan (1W1P) boundaries in a format suitable for both modelers and the general public. This report focuses on the St. Louis River Watershed in northeast Minnesota (Fig. 1). A separate report describes the results for the Zumbro River Watershed in southeast Minnesota (Steenberg and others, 2021). Additional watersheds will be compiled in year two to complete this pilot project in 2022. This report documents the steps taken to compile MGS mapping in the St. Louis River Watershed for the unconsolidated Quaternary sediments and the underlying bedrock topography into a texture-based point model. Methods are described and limitations of the dataset are discussed.

Maps from the County Geologic Atlas (CGA) mapping program were used to compile the most up-to-date geologic information in the St. Louis River Watershed. A full CGA contains two major components, designated as "Part A" and "Part B". Part A is completed by the MGS and includes a package of maps that depict the distribution of sediments and rocks in the subsurface, define their boundaries and geologic names and provide the data used in the creation of the maps (https://cse.umn.edu/mgs/county-geologic-atlas). Supplemental digital and GIS data used in the creation of the maps and all associated geologic products are available for download on our website (https://conservancy.umn.edu/handle/11299/57196). Part B is produced by the Minnesota Department of Natural Resources (MNDNR) and contains detailed groundwater information including hydrogeologic setting, aquifer distribution, pollution sensitivity, groundwater recharge and subsurface flow within the county. Together, this information can be used to make land-use decisions that consider aquifer sensitivity, water quality, and sustainability. This report summarizes the geologic setting and provides a short description of the geologic materials in the watershed. CGA products, however, should be consulted for more detailed information including the geologic setting, geologic data utilized, detailed map unit descriptions, and hydrogeologic properties.

CGAs published prior to the late 2000s generally contain limited GIS data. Modern CGAs include a package of continuous raster surfaces for use in GIS applications for each of the individual map units. Surfaces created represent the elevation of the tops and bottoms of the mapped units, and their thicknesses. A raster is a spatial dataset that consists of a matrix of equally sized cells (or pixels) arranged in rows and columns. Each cell contains an attribute value and location coordinates. They are a powerful GIS tool used to accurately depict the subsurface geologic environment and provide a modeling framework to spatially analyze geology and groundwater.

The St. Louis River Watershed spans five northeast Minnesota counties (St. Louis, Lake, Itasca, Carlton, and Aitkin) and covers an area nearly 3000 square miles (7770 square kilometers). Carlton County is the only county in the watershed with a published CGA (Boerboom and others, 2009). CGA mapping was in-progress for Lake, St. Louis, and Aitkin Counties during this project and preliminary datasets were used for this compilation. CGA mapping has yet to commence in Itasca County, and therefore this project included new subsurface mapping for the small portion of the county that is within the St. Louis River Watershed.

Geologic Setting

The St. Louis River Watershed encompasses a region of particularly complex geology. Located along the southern edge of the Canadian Shield craton, the watershed is floored by Archean igneous and metamorphic rock-types (2.7 Ga), most of which are buried beneath younger Paleoproterozoic foreland deposits of the Penokean Orogen (1.8-2.0 Ga) that form the uppermost bedrock unit across the majority of the study area. Both of these terranes are transected by the Mesoproterozoic Midcontinent Rift Supersuite (1.1 Ga). Mesozoic strata (ca. 95 Ma) and saprolite of varying thickness occur locally, although were once likely more widespread, prior to being largely stripped-away by erosion throughout glacial cycles leading up to the Mid-Pleistocene transition (>0.7 Ma).

Bedrock geology in the St. Louis River Watershed is obscured by unconsolidated Quaternary deposits (<2.6 Ma) that range in thickness, generally between 0 and 350 ft. (107 m.), though may exceed 500 ft. (152 m.) atop areas of low bedrock surface elevation in the vicinity of the St. Louis River freshwater estuary. Areas with the thickest sediments overlie deeply incised bedrock valley systems, several of which cut across the Giants Range topographic high that delineates the northern boundary of the watershed (Fig. 2). Although older sediments are patchily preserved within the deep subsurface, in particular along the southern flank of the Giants Range, most glacigenic materials were deposited during the late Wisconsinan—the most recent glacial episode in North America—and are derived largely from bedrock and pre-existing sediments that originated from areas north (Rainy provenance), northwest (Winnipeg and Riding Mountain provenances), and northeast (Superior provenance) of the study area. Materials of each provenance were transported and emplaced along the southern margin of the

Laurentide Ice Sheet throughout multiple phases of glacial advance and retreat. Sandy loam- to clay loam-textured diamicton (primarily till—i.e., unsorted sediment deposited directly in contact with glacial ice) is the principal glacial deposit within the watershed, though channelized sand and gravel exists, both at the surface and within the subsurface, in the form of ice-contact (eskers, hummocks, kames) and proglacial (outwash) meltwater deposits.

More areally-extensive coarse-grained bedded sediments are spread across the western portion of the study area, where they were deposited as deltaic materials into glacial lakes confined within the Paleoproterozoic Animikie (Pleistocene Upham) basin. Stratified sand and gravelly-sand also trace the perimeter of this basin, forming beach ridges and nearshore lake-bottom sediments—including those associated with glacial lakes formed prior to the last deglaciation that are buried within the subsurface. Thick packages of clay to silty clay overlie till within the central reaches of the basin, having been deposited within pelagic settings of the same glacial lakes. Holocene lacustrine and alluvial deposits form a thin veneer in the vicinity of post-glacial lakes and streams.

Properties of both the unconsolidated Quaternary sediments and Precambrian bedrock in the study area affect regional hydrogeology across the watershed. Most till and fine-grained glaciolacustrine sediments do not readily transmit water, and hence they behave as aquitards that restrict the flow of groundwater into and out of subsurface aquifers. Alternatively, glacigenic sand and gravel deposits tend to be highly transmissive and are typically regarded as potential aquifers capable of storing large volumes of groundwater and yielding adequate flow to a well. These Quaternary sediments, however, are discontinuous and vary in thickness, elevation, and extent over relatively short distances, and hence the majority of water-bearing wells inside the map area are set within fractured bedrock aquifers. Despite this, overlying unconsolidated materials control the rate at which bedrock aquifers are recharged and can influence groundwater chemistry through infiltration. The geotechnical characteristics and distribution of superjacent materials may also impact the sensitivity of unconfined aquifers to potential contaminant sources at the land surface. Presently, there is much effort being expended to investigate these relationships, given the proximity of existing (ferrous) and proposed (polymetallic) mining to state and federal wilderness areas and protected land.

All the various unconsolidated deposits described above that occur within roughly 10 feet (3 meters) of the lowermost soil horizon are depicted as mapped in Fig. 3A. These units were simplified for visualization purposes into five categories that represent sand (sorted coarse-grained sediments), mixed (variable proportions of both sorted and unsorted coarse- and fine-grained sediments), clay (sorted fine-grained sediments), organic-rich peat/wetland sediment, and bedrock (Fig. 3B). Overall, within the St. Louis River Watershed, a total of 68 units were differentiated, including 40 surficial and 34 subsurface units (Table 1) with some units occurring both in the surface and subsurface.

Methods

Bedrock Topography Compilation

Bedrock topography represents the elevation of the bedrock surface and the bottom of the unconsolidated sediments. Bedrock topography is contoured by a geologist in map view at 50-foot (15-meter) contour intervals. Existing datasets, including contours from the Lake, St. Louis, Aitkin, and Carlton CGAs, were compiled and edge-matched. Contours for Itasca were compiled from Jirsa and others (2011), a statewide bedrock map. These contours were transformed into a raster surface using the "Topo to Raster" tool in ESRI ArcMap 10.7.

Watershed-scale Compilation of Quaternary (Unconsolidated) Sediments

To create a seamless surficial geology map across the watershed, 1:100,000 scale geologic contacts from the digital database D-1 (https://mngs-umn.opendata.arcgis.com) were combined with those from more recent maps completed in St. Louis and Lake Counties (Wagner and others, in press a, b). The digital database D-1 contains lines, labels, and polygons that were compiled and edge-matched from all previous MGS Quaternary maps and is a digital companion to the statewide map of Quaternary geology (Lusardi and others, 2019). Unit identifiers from the updated mapping were modified to match the D-1 schema. With the exception of post-glacial materials, all Quaternary deposits are assigned to lithostratigraphic units defined within Johnson and others (2016).

Individual maps that contributed to both the new mapping and the compilations were originally developed from a combination of legacy and remote sensing datasets (i.e., digital aerial photographs, satellite imagery, United States Geological Survey (USGS) 1:24,000 scale topographic maps, and 1-meter (3-foot) spatial resolution LiDAR DEMs), and ground-truthed in the field via documentation and sampling of natural and artificial exposures. Descriptions of near-surface stratigraphy developed from scientific drill-core, water-well cuttings, and soil-auger borings provided additional constraints on that mapping. Field data described above, as well as engineering test borings collected by various organizations, are housed within the Quaternary Data Index (QDI), an internal working database of the MGS. Geologic interpretations were also supported by soil maps in this region (Natural Resources Conservation Service, C2020), and by water-well records stored within the County Well Index (CWI) database. The 68 map units displayed on the surficial geology map and defined within the subsurface, are differentiated on the basis of color, texture, lithology of the very coarse-grained (1-2 millimeters) sand fraction, stratigraphic position, geomorphologic expression, and landscape position (Figs. 3A and 4, Table 1). It is beyond the scope of this report to provide full descriptions of these units, and to place their occurrence within the context of regional glacial history, however the reader is directed to the source materials outlined in this section for complete accounting of all geologic information.

To depict the distribution of Quaternary materials within the subsurface, lines representing continuous base elevations of individual lithostratigraphic units in two-dimensions (x, y) were compiled from existing datasets at regular 5-kilometer (3.1-mile) intervals along 27 east-west trending cross sections. Existing datasets included linework from the 1-kilometer (0.62 meter) cross sections produced for the CGAs of St. Louis, Lake, and Carlton Counties (McDonald et al., in press a, b; Knaeble and Hobbs, 2009). New lines were generated for cross sections within those portions of Aitkin and Itasca counties inside of the St. Louis River Watershed. Unit contacts on the cross sections were edge-matched at county boundaries for consistency. Lines depicting base elevations of sand and gravel units in the source datasets were removed, and intersecting contacts were modified to maintain consistent stratigraphic order throughout the watershed. Examples of interpretations made along one of these cross sections is shown in Fig. 4.

Following compilation of the cross sections, GIS software was used to extract elevation (z) values from vertices along each unit line. These values and their associated 2D locations (x, y) were interpolated into rasters (herein "surfaces") representing the continuous base elevation and areal distribution of each identified lithostratigraphic unit. Surfaces were iteratively modified to ensure a stratigraphic interpretation consistent with the majority of the data, and thereafter processed using basic raster calculations to generate model outputs comprising a set of top and bottom surfaces, and a thickness for each geologic unit.

Texture-based Point Model

The unconsolidated sediments above bedrock, as well as the areas where bedrock is near the surface, are depicted in this dataset as a series of points referred to as a "texture-based point model". Texture is reported based on the percent sand, silt and clay as one of the twelve recognized United States Department of Agriculture (USDA) soil texture classes (Soil Science Division Staff, 2017). These include sand, loamy sand, sandy loam, sandy clay loam, loam, silt loam, silt, silty clay loam, clay, clay loam, sandy clay, and silty clay. For unsorted deposits (i.e., diamicton), only the texture of the matrix (< 2mm fraction) is considered. We have also included sandy gravel and gravelly sand in our descriptions, as these are important properties for modeling groundwater flow in the subsurface, despite not being recognized as official USDA textures. The texture-based point model can be viewed 2-dimensionally or 3-dimensionally in a GIS environment or through our web-based 3D model (Fig. 5, https://arcg.is/1mbDPC). The texture-based point model for our web-based visualization generalizes these textures further into sand, mixed (variable amounts of clay and sand), clay, bedrock, and peat (peat/wetland sediment and water). Table 1 depicts the generalized texture for each unit.

The texture-based point model was created to visualize textures at and below the ground surface, down to bedrock (Fig. 5). The model points are established at 250-meter (820-foot) regularly-spaced intervals with 5-foot (1.5-meter) vertical spacing throughout the watershed. There are more than 1.7 million points in the model. The model was produced in three different modeling stages that were subsequently combined. The three modeling outputs are referred to as the "surficial model", "subsurface model", and the "interpolated model". All modeling processes used the same point matrix spacing. The surficial and subsurface models used the mapping created for this project. The surficial model points, at ground elevation, were intersected with the surficial geology dataset. They were then assigned the respective map unit label. We then applied its associated texture in the attribute table. The subsurface point model matrix was intersected with the 34 subsurface rasters. Points were assigned a Quaternary unit if their elevation was within the elevation range of the top and bottom of a particular Quaternary unit surface. Then they were assigned the texture of that unit.

The interpolated model was constructed with GIS processes by applying ordinary kriging estimation and prediction standard error methods on the current lithology data listed in the CWI stratigraphy table to estimate the likelihood at a given point of sand, clay or a mixed value (Tipping, 2019). Lithology data from CWI was assigned a 'kclass' value of 1 (fine-grained material), 2 (mixed material), or 3 (coarse-grained material). Data was then interpolated using ordinary kriging separately for the likelihood of 'kclass' > 2.5 = sand. Prediction standard error methods were used to limit interpolation based on data density. This method identifies locations where data density is insufficient for the interpolated model process to estimate the likelihood of sand. Remaining points are assigned their likelihood of occurrence in the field 'spot'. Spot values and their distribution were reviewed and compared to the mapped sand from the Lake and St. Louis CGA. For this model, we chose to include points that have a 50% (0.5 spot value) or greater likelihood of sand.

The surficial, subsurface, and interpolated models are separate modeling processes used to estimate the texture at any given point from the land surface down to bedrock. We've included results from all three processes for this watershed. We've also combined the entire set into one matrix of texture points with no overlapping points with the following recommended hierarchy: the surficial model, the interpolated model's sand values (for points with 50% likelihood of sand or greater), and the subsurface model. Because the subsurface model does not contain any units defined as sand and/or gravel, no manually-identified sand bodies are overwritten by the interpolated model. All points are uniquely identified with a 'Unique_ID' attribute that includes their UTM coordinates and elevations so users can query the datasets.

3D Visualization Methods

A 3D geologic model for the St. Louis River Watershed was built using ESRI ArcGIS Pro 2.8 and the data described above (Fig. 5). To produce a 3D block of bedrock, an arbitrary basal bedrock surface was created by subtracting 100 feet (30.5 meters) from the bedrock topography surface. Both the bedrock topography and basal bedrock surface were then converted into triangulated irregular network (TIN) datasets using the "Raster to TIN" tool. The TINs were configured with a Z Tolerance value of 20 (to balance precision with 3D drawing performance) and a Z factor of 6.096 (to convert the z-axis elevation values to meters while exaggerating the scale 20 times). The TINs, along with the polygon delineating the St. Louis River Watershed, were used to create a 3D multipatch of the bedrock topography surface using the "Extrude Between" tool. Prior to this, the St. Louis River Watershed polygon was split into multiple polygon subdivisions using the "Subdivide Polygon" tool to minimize 3D data outliers that can occur during the extrusion process.

For the Quaternary, the surficial geology polygons were reclassified based on the USDA texture defined for each unit into five generalized textural categories (clay, mixed, sand, peat [peat/lake sediment and water], and bedrock) (Fig. 3B, Table 1). Each of the five textural categories were then exported as 2D polygon layers and uploaded to ArcGIS Online as tile layers to optimize model loading. To visualize the subsurface data, a subset of the texture-based point model (1000 x 1000 meters [3281 x 3281 feet] and 20 feet [6.1 meters] in the vertical) was created and its vertical z-axis values converted to meters and exaggerated 20 times. Each of the five textural categories were then exported as 3D point layers.

The derivative bedrock and Quaternary data were compiled into an ArcGIS Pro Local Scene with the "Ground" reference layer set as a 20x vertically-exaggerated, 30-meter (98-foot) land surface DEM of the St. Louis River Watershed. This DEM was originally sourced from 1-meter (3-foot) LiDAR data supplied by the MNDNR and elevation values were converted from feet to meters. The ArcGIS Pro Local Scene was then shared to ArcGIS Online as a web scene and imported into a web app, where further adjustments were made for accessibility and optimization.

Using the Web-based 3D Model

The web-based 3D model (https://arcg.is/1mbDPC) is meant to be a visualization tool for water planners, other state agencies involved in the GRAPS process, and the general public, and is made readily accessible in a browser, requiring no GIS software. The model is separated into three parts: surficial glacial geology, subsurface glacial geology, and bedrock geology. The surficial and subsurface glacial geology has been simplified into five textural categories of clay, mixed, sand, peat (peat/lake sediment and water) and bedrock. Each category is a separate layer in the model that can be turned on/off independently of the others. The surficial glacial geology is shown as 2D polygons and represents the unconsolidated glacial sediments within a few meters of the land surface and where bedrock is within a few meters of the land surface. The polygons are shown with slight transparency to allow users to peer through them at underlying data. Below these polygons are the regularly spaced, 3D point data representative of the subsurface glacial geology from the base of the surficial deposits down to the top of bedrock. Below the regularly spaced point data lies the bedrock topography of the Precambrian bedrock in the St. Louis River Watershed. To better visualize thinner geologic units at this scale, the 3D model is exaggerated 20 times in the vertical and the surficial geology, subsurface geology and bedrock datasets are vertically offset from one another and the ground surface to prevent data overlap. Furthermore, a Geographic References layer and three different Basemap layers are included for reference. The Geographic References layer is an overlay of geographic boundaries, roads, city names and various other geographic features, so the user can readily identify or search by surface areas of interest.

Upon each initial access, the web-based 3D model loads from a plan- (or map-) view perspective. You can return to this view by clicking the *Home* button on the left side of the map window. You can zoom in or out using the buttons on the left side of the map window, by scrolling a mouse wheel, or by pinching in/out with two fingers when viewed from a touch-compatible device. To rotate the 3D model, right-click and drag your cursor within the map window or press with two fingers and drag across the map window when viewed from a touch-compatible device. You can also change your primary navigation setting by clicking on the *Navigate* button on the left side of the map window.

Above the *Navigate* button is a *My Location* button that will detect your physical location and zoom the map to it based on available network or GPS location. You can use the *Search Box*, located in the upper right corner, to zoom to a specific address or geographic location. Just below the *Search Box* is the *Reset Compass Orientation* button (to reset the compass orientation of the map view) and the *Full Screen* button (to view the 3D web model in full screen).

To the left of the map window lies the widget window containing 5 widgets: *Legend*, *Layer List*, *Measurement*, *Share* and *About*. The *Legend* acts as the map key, indicating the symbol type and color for features currently displayed in the map window. This is especially useful for discerning the five textural categories of the Quaternary data, and is the primary widget shown upon each initial access to the web model. The *Layer List* shows all the available layers contained within the 3D web model and gives users the ability to turn on and off each layer by clicking the checkbox. Note that only one Basemap layer can be turned on at a time. The *Measurement* widget contains tools that allow you to measure the area or distance of a user-defined polygon or line in the map window. The *Share* widget contains a shortened URL that can be copied and shared with others to quickly access this 3D web model, along with options to embed this model on a separate website. Lastly, the *About* widget gives a summary of the model, its intended purpose, and acknowledgement of funding.

Discussion and Future Work

Ongoing mapping in St. Louis and Lake Counties for the CGA program provided an opportunity to test our methods for this watershed approach and compare them to the CGA products. For the watershed approach we reduced the number of cross sections drawn by the geologist, increasing their spacing to 5 kilometers (3.1-miles). Choosing a cross section spacing of 5-kilometers (3.1-mile) rather than 1-kilometer (0.62-mile) reduces time spent on mapping, however, it increases the oversimplification and linearity of unit distribution in map view. We also chose to create unit surfaces of the Quaternary unit tops and bottoms of only till and fine-grained materials in the subsurface and used the interpolated model to capture the most recent sand distribution information available from CWI to fill in the texture-based point model. There was trial-and-error involved in running the interpolated model to capture the sand that was both described by a driller in CWI and mapped by the geologist. In northeast Minnesota, many of the subsurface glacial till units mapped by a geologist are rocky and described by a driller as sandy. Keeping sand from the interpolated model with a 50% probability of occurrence most accurately depicted sand in the subsurface that matched the geologist's interpretation.

The modeling process we use to create unit surfaces of the Quaternary units from cross sections (as opposed to manually mapping these surfaces in plan-view) has some unintended artifacts that have been brought to light in creating a texture-based point model. Our modeling process produces unit surfaces that match the elevation and extents of the geologist's drawn cross sections very well along the cross-section line. Between the cross-section lines, our current modeling and interpolation methods within ArcMap overgeneralizes the elevation and extent of units to make a continuous surface. A second step to this process was needed for the base surfaces (bottom elevation of a unit) corresponding to the deepest (oldest) unit in the stratigraphic stack at any given location to be recalculated such that their elevation value equaled the underlying bedrock topographic surface. This reduced the volumetric proportion of the model space that was unassociated with a basal Quaternary unit, thereby eliminating a significant number of basal null values within the subsurface point model that was generated by sampling this space.

Next year, we intend to develop improved methods for interpolating between cross section lines. This may include mapping the Quaternary fine-grained sediments in plan-view by manually contouring till unit bases. This will be a challenge due to the complexity of these deposits but is needed to correct for the oversimplification of map unit distribution between 5-kilometer (3.1-mile) cross section lines. Working in watershed areas that already have CGA Quaternary cross sections completed at 1-kilometer (0.6-mile) spacing should aid in developing this process.

The St. Louis River Watershed model is based on the USGS HUC-8 boundary that differs slightly from the BSWR 1W1P boundary. The HUC-8 boundary was chosen to limit quantification of water budget, both surface water and groundwater, to the watershed boundary itself. Future efforts with the GRAPS program will also include putting together more supporting text from a hydrogeologic perspective to be presented along with the model for the general user to make sense of the information and how it may apply to their resource conservation work.

List of Figures and Tables

Figure 1.

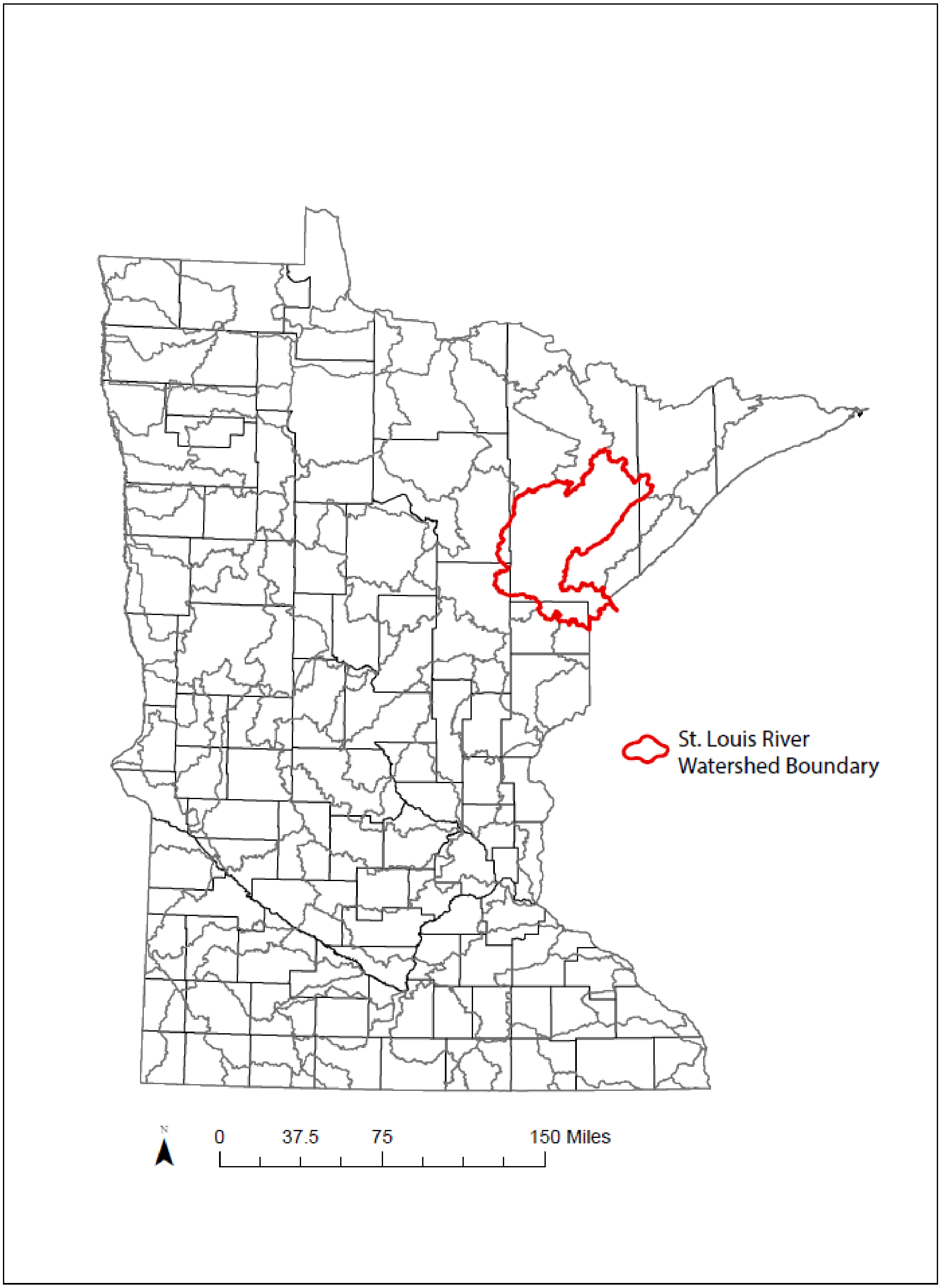
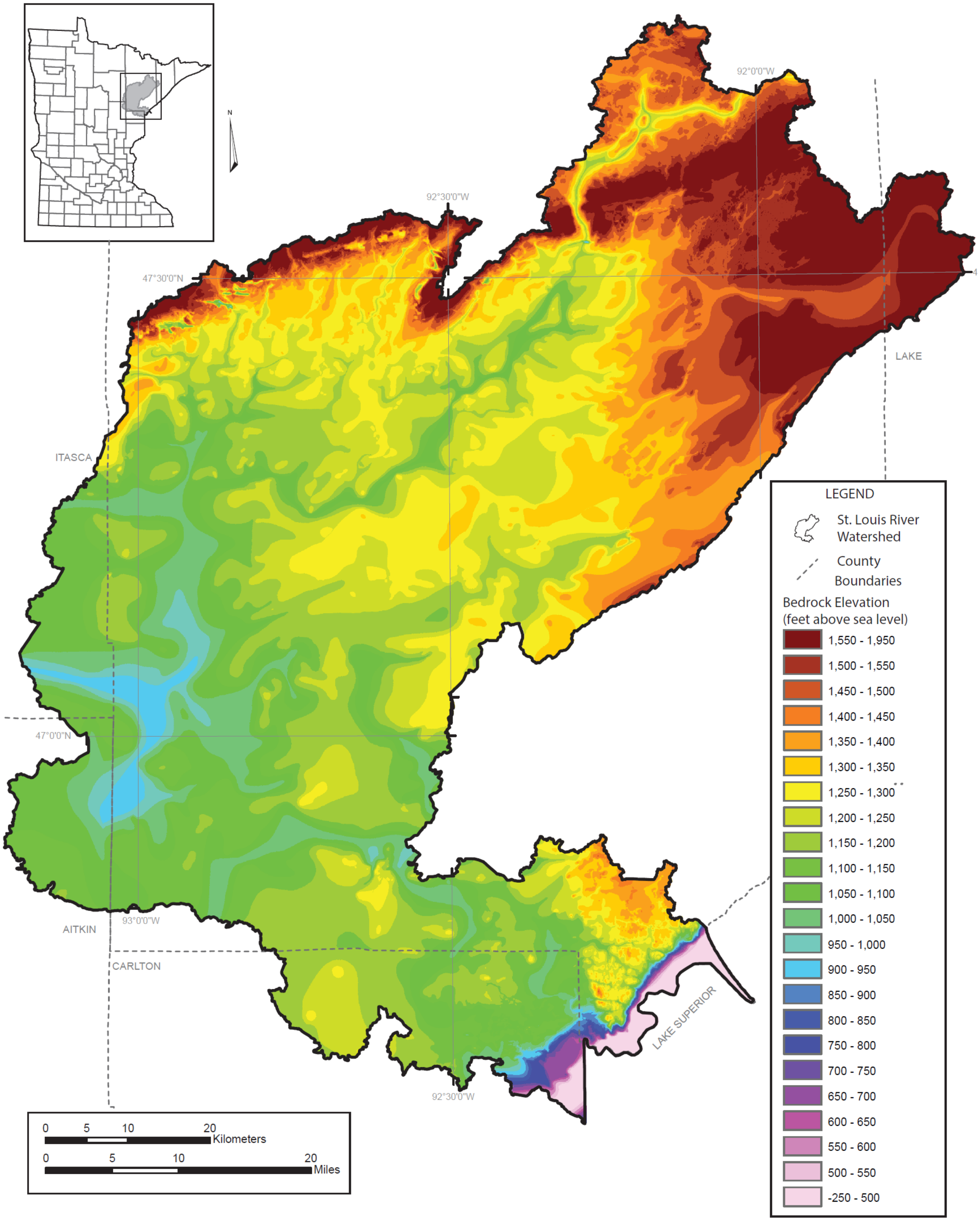


Figure 2.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St. Louis River Watershed
County Boundaries
Bedrock Elevation (feet above sea level)
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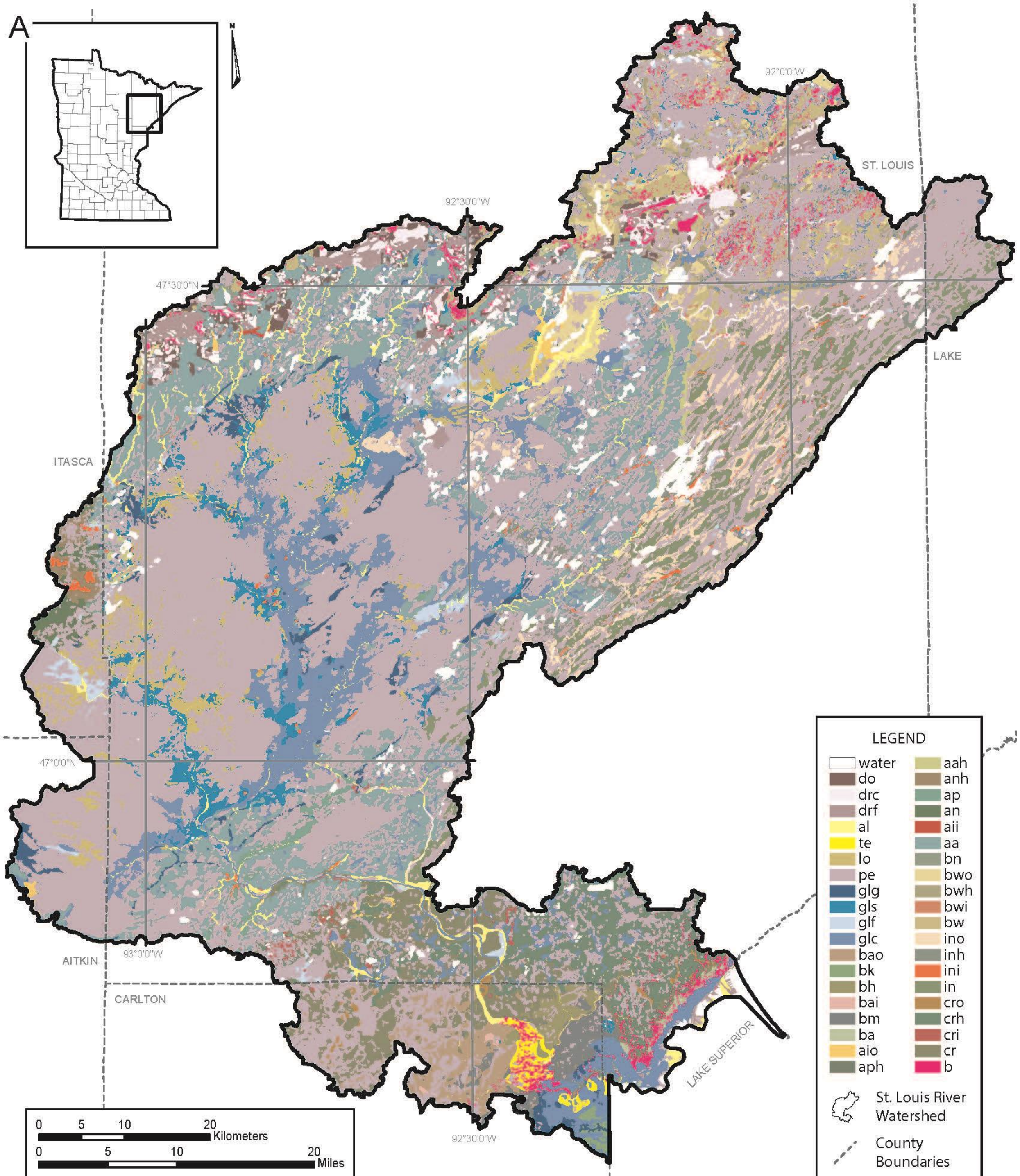
Figure 3A.



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St. Louis River Watershed
County Boundaries
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Figure 3B

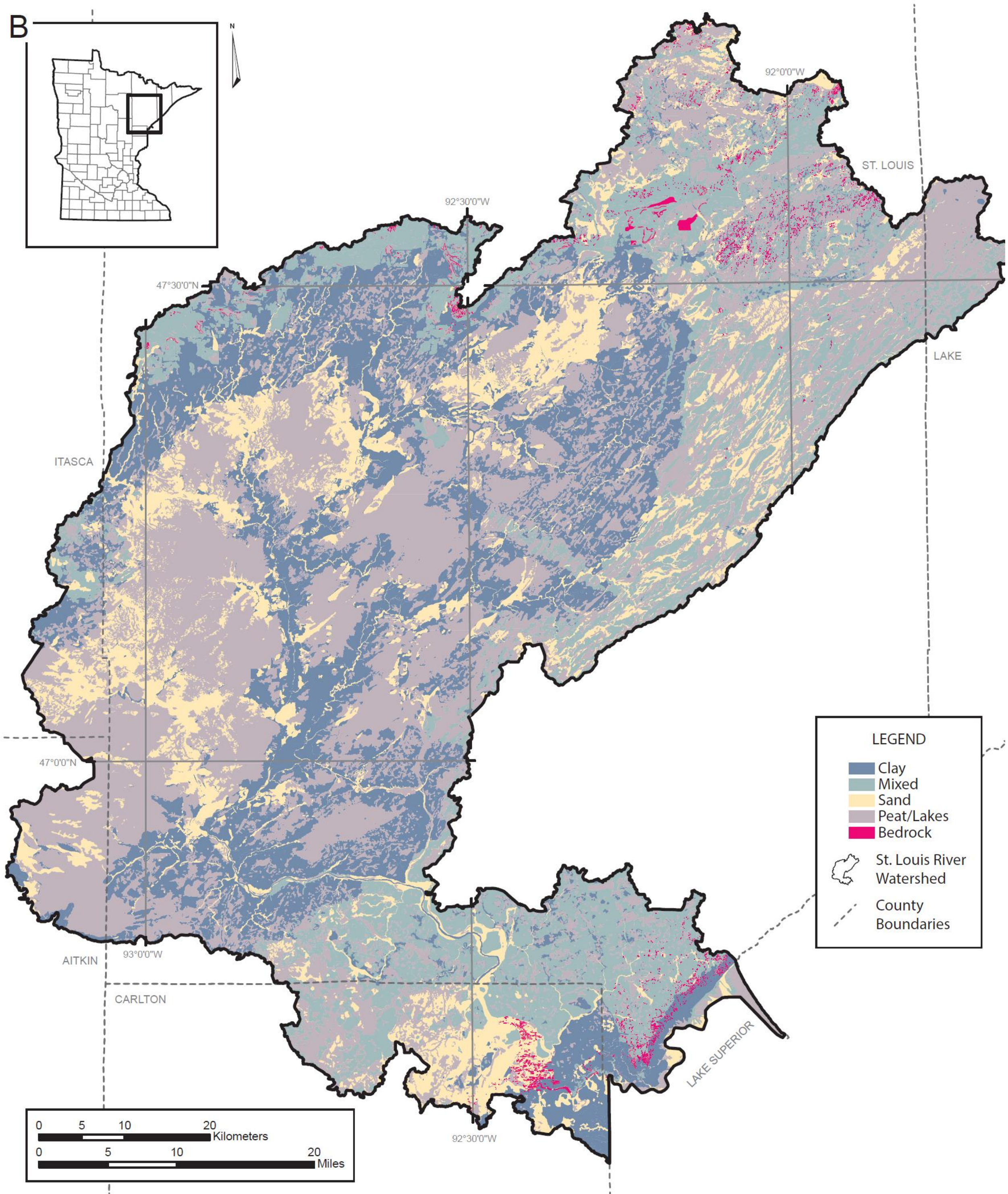
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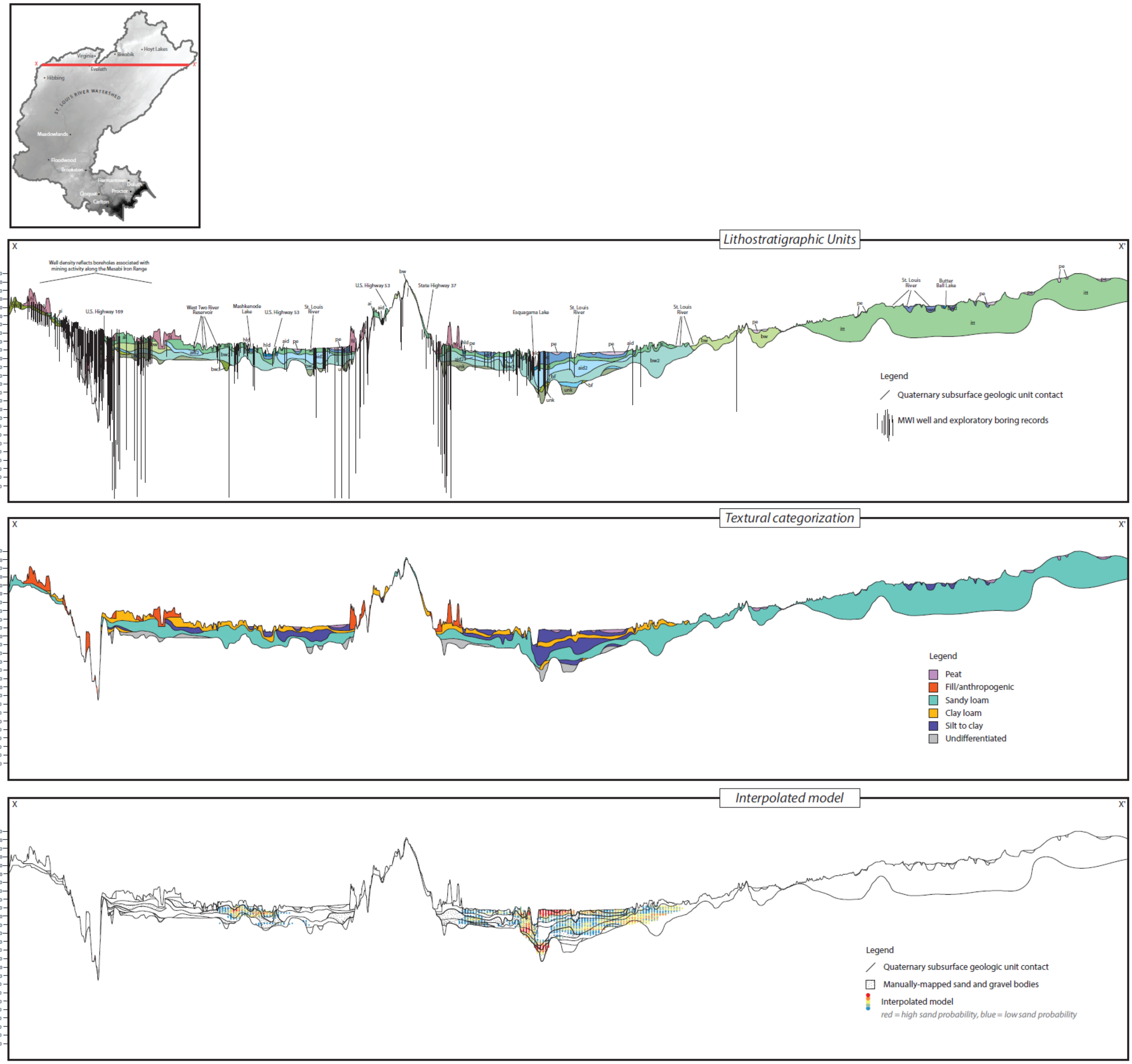
Figure 4.



Lithostratigraphic Units
Textural categorization
Interpolated model
Legend
Quaternary subsurface geologic unit contact
MWI well and exploratory boring records
Legend
Peat
Fill/anthropogenic
Sandy loam
Clay loam
Silt to clay
Undifferentiated
Legend
Quaternary subsurface geologic unit contact
Manually-mapped sand and gravel bodies
Interpolated model
red = high sand probability, blue = low sand probability

Figure 5.

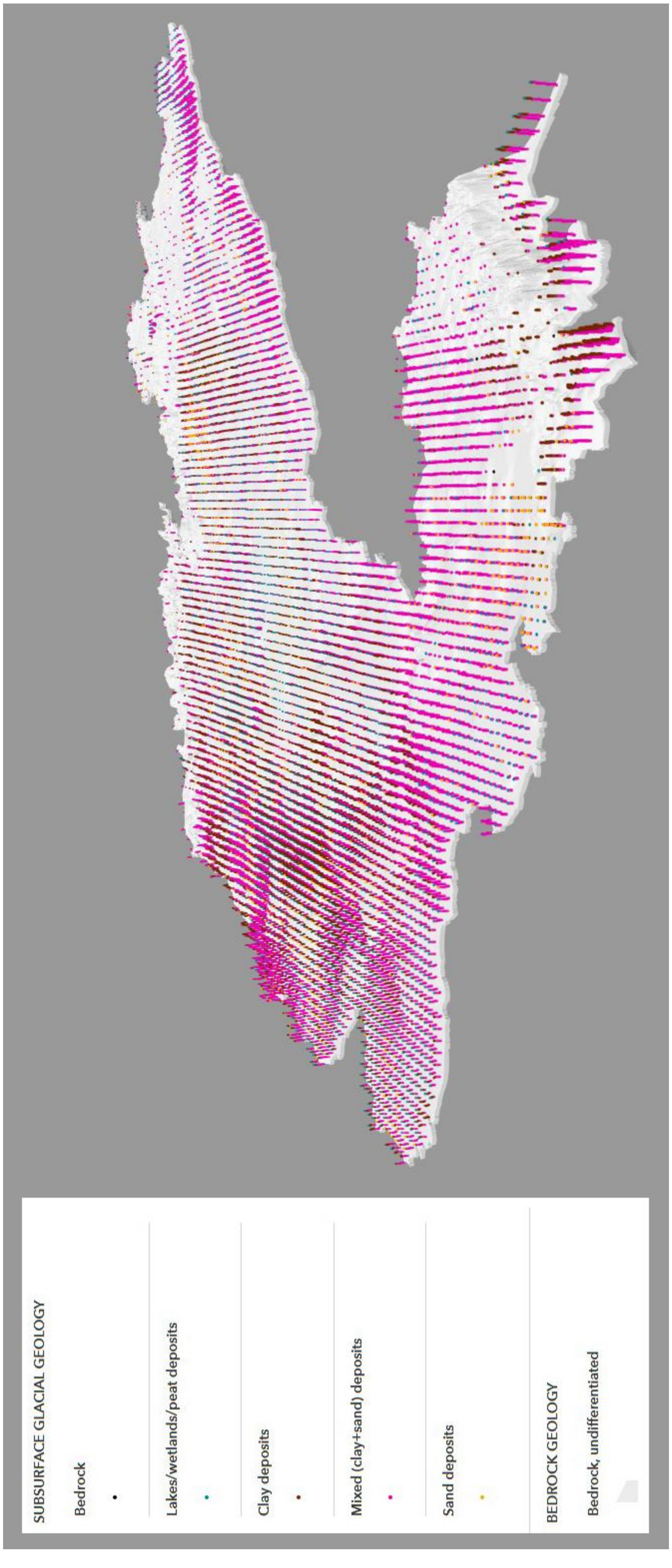

SUBSURFACE GLACIAL GEOLOGY
Bedrock
Lakes/wetlands/peat deposits
Clay deposits
Mixed (clay+sand) deposits
Sand deposits
BEDROCK GEOLOGY
Bedrock, undifferentiated

Table 1.

Map type		Unit Code	Lithostratigraphic Formation/Member	Unit type	USDA texture	Generalized online 3D model texture
	Surficial	water	Post-glacial	Water	n/a	Lakes/Wetlands/Peat
	Surficial	do	Post-glacial	Overburden dump mound	n/a	Mixed
	Surficial	drc	Post-glacial	Rock dump mound	n/a	Mixed
	Surficial	drf	Post-glacial	Fine-grained tailings basin	n/a	Mixed
Subsurface		fil	Post-glacial	Fill	n/a	Mixed
	Surficial	al	Post-glacial	Alluvium	Loamy sand	Sand
	Surficial	te	Post-glacial	Terrace alluvium	Loamy sand	Sand
	Surficial	lo	Post-glacial	Eolian	Loamy sand	Sand
Subsurface	*Surficial*	pe	Post-glacial	Peat/wetland sediment	n/a	Lakes/Wetlands/Peat
Subsurface		hld	Post-glacial	Lacustrine	Silty clay	Clay
	Surficial	glg	n/a	Glaciolacustrine	Sandy gravel	Sand
	Surficial	gls	n/a	Glaciolacustrine	Loamy sand	Sand
	Surficial	glf	n/a	Deltaic	Loamy sand	Sand
	Surficial	glc	n/a	Glaciolacustrine	Silty clay	Clay
Subsurface		bad	Barnum Formation	Glaciolacustrine	Silty clay	Clay
	Surficial	bao	Barnum Formation	Outwash	Sand	Sand
	Surficial	bk	Barnum Formation, Knife River Member	Till/Glaciolacustrine	Clay loam	Clay
	Surficial	bh	Barnum Formation	Complex	Loam	Mixed
	Surficial	bai	Barnum Formation	Ice contact glaciofluvial	Sandy gravel	Sand
	Surficial	bm	Barnum Formation, Moose Lake Member	Till	Clay loam	Clay
Subsurface	*Surficial*	ba	Barnum Formation	Till	Clay loam	Clay
Subsurface		aid	Aitkin Formation	Glaciolacustrine	Silty clay	Clay
	Surficial	aio	Aitkin Formation	Outwash	Sand	Sand
Subsurface		bd	Blackduck Formation	Till	Clay loam	Clay
	Surficial	aph	Aitkin Formation, Prairie Lake Member	Complex	Loam	Mixed
	Surficial	aah	Aitkin Formation, Alborn Member	Complex	Clay loam	Mixed
	Surficial	anh	Aitkin Formation, Nelson Lake Member	Complex	Clay loam	Mixed
Subsurface	*Surficial*	ap	Aitkin Formation, Prairie Lake Member	Till	Loam	Clay
	Surficial	an	Aitkin Formation, Nelson Lake Member	Till	Clay loam	Clay
	Surficial	aii	Aitkin Formation	Ice contact glaciofluvial	Gravelly sand	Sand
	Surficial	aa	Aitkin Formation, Alborn Member	Till	Clay loam	Clay
Subsurface		ai	Aitkin Formation	Till	Clay loam	Clay

Subsurface		bwd	Boundary Waters Formation	Glaciolacustrine	Silty clay	Clay
Subsurface		ind	Independence Formation	Glaciolacustrine	Silty clay	Clay
Subsurface		crd	Cromwell Formation	Glaciolacustrine	Silty clay	Clay
Subsurface	*Surficial*	bn	Boundary Waters Formation, Nashwauk member	Till	Clay loam	Clay
Subsurface		aid2	Aitkin Formation	Glaciolacustrine	Silty clay	Clay
	Surficial	bwo	Boundary Waters Formation	Outwash	Gravelly sand	Sand
	Surficial	bwh	Boundary Waters Formation	Complex	Sandy loam	Mixed
	Surficial	bwi	Boundary Waters Formation	Ice contact glaciofluvial	Sandy gravel	Sand
Subsurface	*Surficial*	bw	Boundary Waters Formation, Mesabi member	Till	Sandy loam	Mixed
Subsurface		bwd2	Boundary Waters Formation	Glaciolacustrine	Silty clay	Clay
	Surficial	ino	Independence Formation	Outwash	Gravelly sand	Sand
	Surficial	inh	Independence Formation	Complex	Sandy loam	Mixed
	Surficial	ini	Independence Formation	Ice contact glaciofluvial	Sandy gravel	Sand
Subsurface	*Surficial*	in	Independence Formation	Till	Sandy loam	Mixed
	Surficial	cro	Cromwell Formation	Outwash	Gravelly sand	Sand
	Surficial	crh	Cromwell Formation	Complex	Loam	Mixed
	Surficial	cri	Cromwell Formation	Ice contact glaciofluvial	Sandy gravel	Sand
Subsurface	*Surficial*	cr	Cromwell Formation	Till	Loam	Mixed
Subsurface		ind2	Independence Formation	Glaciolacustrine	Silty clay	Clay
Subsurface		bw2	Boundary Waters Formation, Mesabi Member	Till	Sandy loam	Mixed
Subsurface		aid3	Aitkin Formation	Glaciolacustrine	Silty clay	Clay
Subsurface		in2	Independence Formation	Till	Sandy loam	Mixed
Subsurface		in3	Independence Formation	Till	Sandy loam	Mixed
Subsurface		cr2	Cromwell Formation	Till	Loam	Mixed
Subsurface		in4	Independence Formation	Till	Sandy loam	Mixed
Subsurface		cr3	Cromwell Formation	Till	Loam	Mixed
Subsurface		ind3	Independence Formation	Glaciolacustrine	Silty clay	Clay

Subsurface	bw3	Boundary Waters Formation, Mesabi Member	Till	Sandy loam	Mixed
Subsurface	bwd3	Boundary Waters Formation	Glaciolacustrine	Silty clay	Clay
Subsurface	bf	Big Fork Formation	Till	Clay loam	Clay
Subsurface	bf2	Big Fork Formation	Till	Clay loam	Clay
Subsurface	bw4	Boundary Waters Formation, Mesabi Member	Till	Sandy loam	Mixed
Subsurface	bw5	Boundary Waters Formation, Mesabi Member	Till	Sandy loam	Mixed
Subsurface	unk	n/a	Unknown	n/a	Mixed
Surficial	b	n/a	Bedrock	n/a	Bedrock

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